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Gravitational fragmentation of a filamentary molecular cloud using SPH

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We investigate the fragmentation of self-gravitating filamentary molecular clouds using 3D simulations performed with the PHANTOM Lagrangian smoothed particle hydrodynamics code. We assume uniform finite filaments with different total masses which are thermally subcritical, critical and supercritical. Sink particles are used as a proxy for dense cores. We find that the mass storage of the filament is a vital agent that can determine its ongoing fragmentation. Our results show that the two less massive models (thermally subcritical and critical) exhibit two dense cores at the final stage of their evolution, while the most massive one (thermally supercritical) harbor many dense cores. We also study the fragmentation of filaments with the same properties as their former counterparts, but with a sinusoidal density perturbation. The results show that the perturbation can affect both the fragmented and the less-dense surrounding gas.

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I. INTRODUCTION

It is widely believed that stars form in molecular clouds (MCs)(see McKee, Christopher F. and Ostriker, Eve C. [1] for a review) which are found ubiquitously in the form of filamentary structures. The importance of interstellar filamentary clouds for star formation has came into attention by Schneider and Elmegreen [2]. Recently, the *Herschel* observations has uncovered the filamentary structure in molecular clouds (e.g André *et al.* [3]).The revealed Herschel observations show that these filaments have a universal characteristic width of ~ 0.1 pc and a Plummer-like density profile [4].

There are a number of numerical studies on the evolution and stability of filamentary structures. In this work we explore the global collapse and fragmentation of finite gas cylinders (hereafter filaments) with different masses which puts them in three regimes namely thermally subcritical, critical and supercritical. An infinite thermally subcritical filament is supported by its internal gas pressure against its self-gravity, however, for a supercritical one, the gas pressure is not supportive enough to prevent the filament from collapsing and fragmenting. The paper is organized as follows: In section 2, we present an overview of the numerical methods and the initial conditions applied in the simulation. In section 3 we discuss our results and conclude.

II. NUMERICAL METHODS AND INITIAL CONDITIONS

A. SPH and PHANTOM

smoothed particle hydrodynamics (SPH) is a Lagrangian method based on particles introduced and formulated for the first time by Gingold and Monaghan [5]. In this method particles are identified with mass m_i, position $\mathbf{r}_i$, velocity $\mathbf{v}_i$, internal energy u_i and smoothing length h_i (where i is the particle label). Except the gravity, all the forces are account only in the radius $r = 2h_i$ of particle i and the Kernel function as follows can determine the amount of impression:

$$\rho(\mathbf{r}) = \sum_{i=1}^{N} m_i W(|\mathbf{r} - \mathbf{r}_i|, h), \tag{1}$$

where W is the smoothing kernel. The kernel function is selected to have compact support within the range $|\mathbf{r} - \mathbf{r}_i| = [0, 2h]$, so that N represents the number of neighboring particles within a distance $2h$ of $\mathbf{r}$. In this case there is no need for grid or any symmetry and the mass continuity is resolved all the time automatically. All the equations of state could be solved through an arbitrary position r by calculating the summation impact of every particle j which are located in r_j and overlapping their Kernel function regarding r.

B. Sink Particles

Sink Particles introduced for the first time by Bate *et al.* [6] to calculate star formation process in initial collapsing phase. High densities and short dynamical time leads to raise the computational expenses to follow the evolution of protostars at the time comparable to the molecular cloud free fall time. Instead, over a critical density a sink particle is created. In this paper the critical density is $10^{-17}\, g\, cm^{-3}$. The SPH gas particles within the radius of 120AU are replaced with the same mass and angular momentum. This particle is replaced with SPH gas particles within radius 120AU with the same mass and angular momentum. These particles are affecting each other only by gravity and accretion. Therefore all the particles with angular momentum less than needed to rotate on the circular orbit around the r_{acc} inevitably accrete on the central sink particle.

C. Numerical methods

This is the first application of PHANTOM to filamentary fragmentation. We present 3D simulations of filaments using PHANTOM SPH code [7] including self-gravity. We apply the critical mass of the filament regarding to resolve Jeans mass and accordingly Jeans length:

$$\lambda_{\rm J} = \sqrt{\frac{\pi c_{\rm s}^2}{G\rho}} \tag{2}$$

where c_s is the sound speed and G the gravitational constant. The gas is initially isothermal (see eg relations (6)) at a temperature of 15 K, which agrees well with temperatures observed in a number of filaments . If the density exceeds the value of

$$\rho_{\rm sink} = 10^{-17}\,{\rm g\,cm^{-3}} \tag{3}$$

gas particles start to accrete within a radius of 120 AU and create the sink particle. The mean molecular weight in this paper is set to $\mu_{\rm mol} = 2.38$

D. Initial conditions

In this paper we investigate the evolution of a filament of radius 0.1 pc and length of 1.5 pc in a box with dimensions at 2.4 and 0.4 pc to avoid the artificial fragmentation and the overlap of the filaments in the periodic dimension of the box. One of the most important parameters in filaments is the mass per unit length which is defined as the following:

$$(M/L)_{\rm crit} = \frac{2c_{\rm s}^2}{G}\,, \tag{4}$$

The critical density that filament starts to collapse and create the sink particles with this particular mass per unit , here is assumed as $10^{-17} g\,cm^{-3}$. At the radius of 120 AU the gas particles start to accrete on the sink particle. Whereas the density reaches the value of $\rho_{\rm sink} = 10^{-13}\,{\rm g\,cm^{-3}}$ the opacity limit occurs and the isothermal equation of state is no more valid, thus the code uses the barotropic equation of state:

$$P = K\rho^{\gamma} \tag{5}$$

where γ is as follows,

$$\begin{aligned} \gamma &= 1.4, & 10^{-13} &\le \rho < 10^{-10}\,{\rm g\,cm^{-3}}, \\ \gamma &= 1.1, & 10^{-10} &\le \rho < 10^{-3}\,{\rm g\,cm^{-3}}, \\ \gamma &= 5/3, & \rho &> 10^{-3}\,{\rm g\,cm^{-3}}, \end{aligned} \tag{6}$$

The value of K is considered equal to the square of the isothermal sound speed c_s at the densities lower than the critical one while it changes after passing the critical density which allows the pressure to be a continuous function of density.

In this work we have the uniform density, and since the Ostriker density Ostriker, J. [8] at the 0.1 parsec is 0.1 central density then our chosen density can be reliable. Our fiducial models with three different filament masses per unit at 30, 37 and 50 solar mass are chosen. The perturbation wave length we apply is 0.05 times of the primary one to study the evolution of the filament and fragmentation process through considering the perturbation and comparison the sink creation time and the evolution time with respect to the various mass per units.

In this step, we show all simulations with their corresponding parameters in a table to compare. All needed ones from mass per unit of the filament to sound speed and the Jeans length calculated and tested separately.

III. RESULTS AND CONCLUSIONS

We performed SPH simulation using the PHANTOM coed to investigate filament fragmentation in different initial conditions. To see how the fragmentation of a filament can be affected by its mass storage, filaments with masses of 30, 37 and 50 $M_\odot$ are considered. It should be noted that for an isothermal infinite filament in hydrostatic equilibrium and the temperature of 15 K, the critical mass is $\simeq$ 24 $M_\odot$/pc. So, our filaments with masses of 30, 37 and 50 $M_\odot$ are thermally subcritical, marginally critical and supercritical. Since in our simulations, filaments are globally collapsing, the computation time could be very large. This usually could be happened if the density exceeds the critical density threshold for creation of sink particles, while because other conditions are not satisfied, no sink particle is formed. For this reason, simulations are terminated ($t_{\rm end}$) a few ten thousand years after formation of the first sink particle ($t_{\rm form}$) (see table. for more details).

Fig.1 demonstrates evolution of a thermally sub- (left), marginally- (middle) and supercritical (right) filament, from up to down at $t = 0$, $t_{\rm form}/2$, $t_{\rm form}$ and $t_{\rm end}$. The colorbar shows the gas column density in logarithmic scale. Sink particles are shown by small white circles in a sense that their radii indicate the accretion radius. At the very beginning of simulations, all three filaments started to collapse, both radially and also along their major axis, but the supercritical filament is the most rapidly collapsing one. Moreover, sink particles are crated firstly at two edges of each of three filaments. This is a known phenomenon which is observed in other works too [e.g. 9]. It is completely obvious that at the onset of sink creation, the subcritical filament has the largest radius, while the supercritical filament is the thinner one. At $t_{\rm end}$, the boundary of subcritical filament is shrunk, so that it seem like a narrow line with two cores at its two

TABLE I: Specification of simulations of filaments with a length of 1.5 pc and the radius of 0.1 pc. We list the total initial model mass, initial number of particles within the filament, mass per unit length, Jeans length, perturbation amplitude, free fall time, number of sink particles, first sink creation time and the time the simulation ends. The first three rows denote specification of models without initial perturbation and the next three rows denote to perturbed models.

Total mass ($M_\odot$)	N	$\frac{(M/L)_{\rm fil}}{(M/L)_{\rm crit}}$	$L_{\rm jeans}$ (pc)	A	$t_{\rm ff}$ (Kyr)	# SP	$t_{\rm form}$ (Myr)	$t_{\rm end}$ (Myr)
30	300000	0.83	0.244	no	320.690	2	0.84	1.15
37	300000	1.02	0.244	no	288.766	2	0.43	0.60
50	300000	1.38	0.244	no	248.406	54	0.29	0.52
30	300000	0.83	0.244	0.05	320.690	2	0.82	0.95
37	300000	1.02	0.219	0.05	288.766	11	0.47	0.56
50	300000	1.38	0.189	0.05	248.406	60	0.3	0.43

ends. This is also the case for the supercritical filament, but it was to be able to form 54 sink particles throughout its length.

We repeat the previous simulations, but now for initially perturbed distributions. The density of the filaments are perturbed as

$$\rho = \rho_0 + \frac{A\rho_0\lambda_J}{2\pi}\left(\sin\left[\frac{2\pi z}{\lambda_J}\right]\right), \tag{7}$$

where A is the amplitude of the perturbation, z is the horizontal coordinate and λ_J is the Jeans wavelength which is taken as 0.75 pc [10, 11]. By this form of sinusoidal perturbation, each filament will has two overdensities at $\pm$l/2 where $\pm$l are the filament ends. We take $A = 0.05$. Except density, the rest of filament properties are all the same. Fig.2 depicts the evolution of these perturbed filaments. Compared to the unperturbed state, one can observed that in the perturbed subcritical filament, the sink pair is appeared a few thousand years later, but in the marginally- and supercritical filaments, the initial sink pair is formed a few thousand years earlier. Interestingly the subcritical filament develops an oblate pattern at $\mathrm{t_{end}}$. At this time the marginally critical filament has two short narrow dense region at its end with 11 sink particles and a wider region at its center. The supercritical filament has a short narrow dense region with 10 sink particles, while its two ends is completely fragmented to 50 sink particles.

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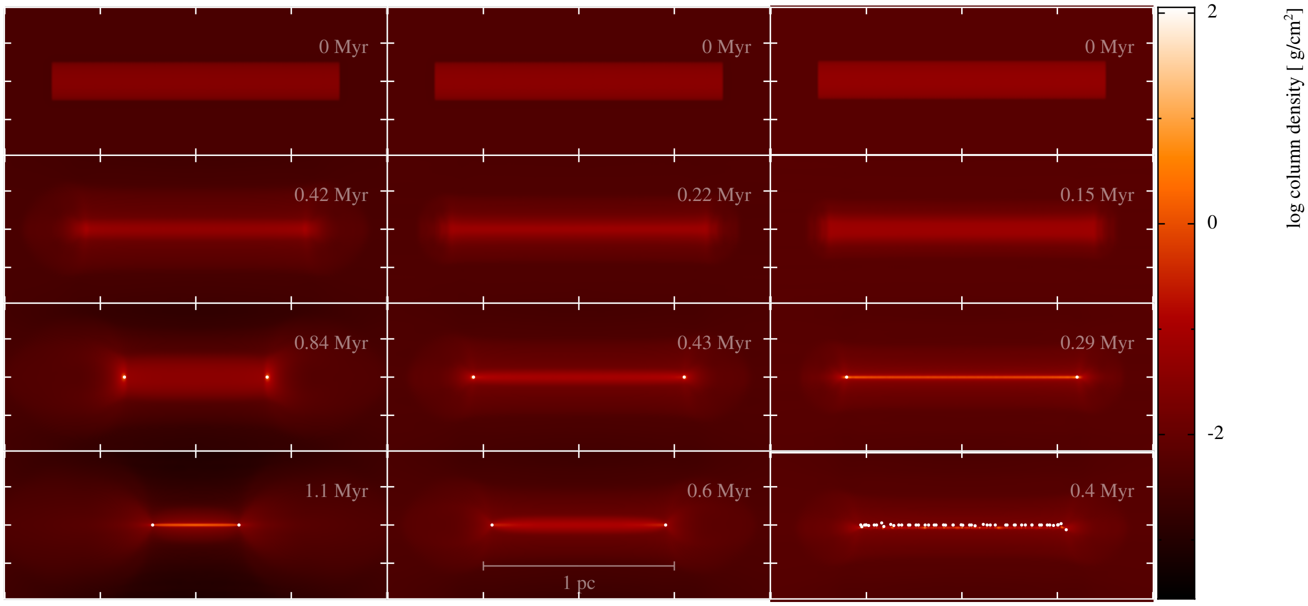

FIG. 1: Time evolution of the column density of the filaments from up to down at t = 0, $t_{form}/2$, t_{form} and t_{end}. The corresponding times for all models are written in each snapshot. Columns show the thermally sub- (left), the marginally- (middle) and the supercritical (right) filaments respectively. The white small circles indicate the sink particles. The length-scale is 1 pc and is the same in all snapshots.

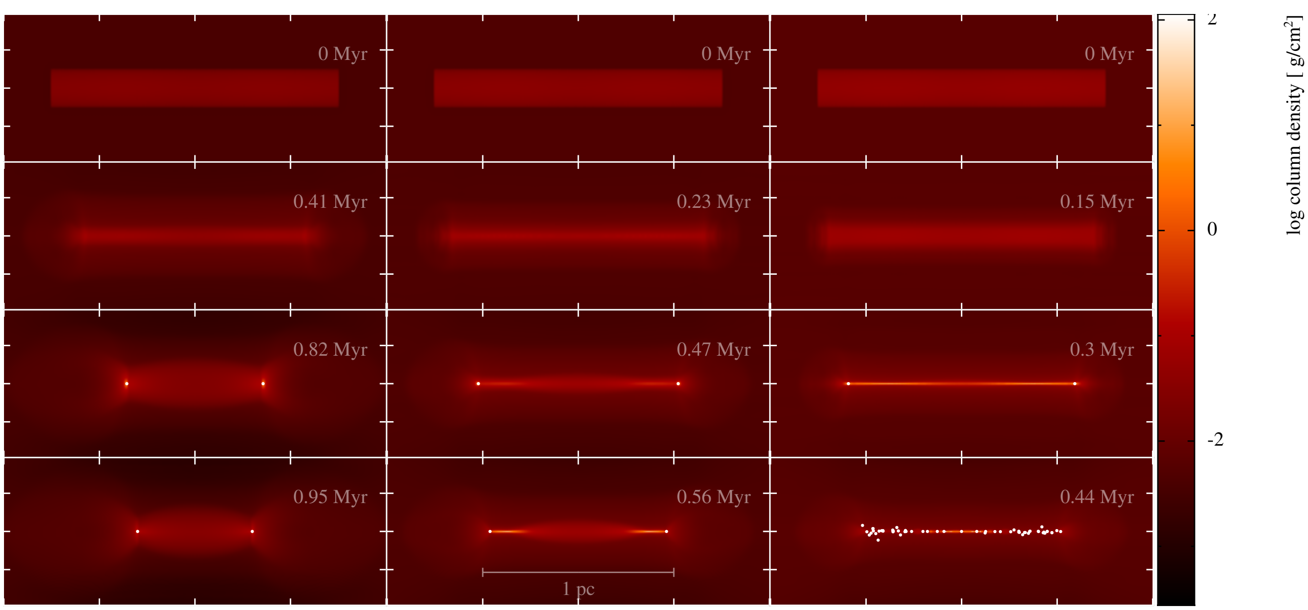

FIG. 2: Same as the fig. 1, but for the perturbed filaments.